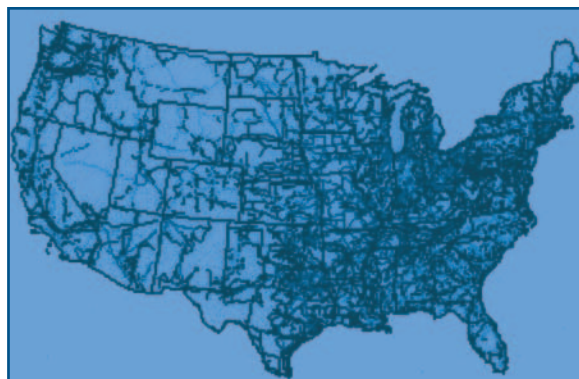


2.0 Program Benefits¹

The Hydrogen Fuel Initiative is designed to reverse America's growing dependence on foreign oil by developing the technology for hydrogen-powered fuel cell vehicles and the infrastructure to support them. This approach was chosen not only because of the energy security benefits associated with a transportation fuel that can be produced domestically from a diversity of feedstocks, but also because of the potential environmental benefits in transportation applications and stationary markets.

2.1 Energy Security

The U.S. currently imports more than half of its oil (compared to only a third during the 1973 oil crisis), and imported oil is expected to increase as demand continues to rise and domestic oil production continues to decline. In addition to crude oil import concerns, current U.S. oil refining is at nearly 97% capacity, and further expansion of domestic U.S. refining capacity is hindered due to environmental constraints (American Petroleum Institute). As a result, the growing U.S. oil consumption beyond 2004 will be supplied primarily from refined fuel imports versus crude oil imports (see Figure 2.1.1).

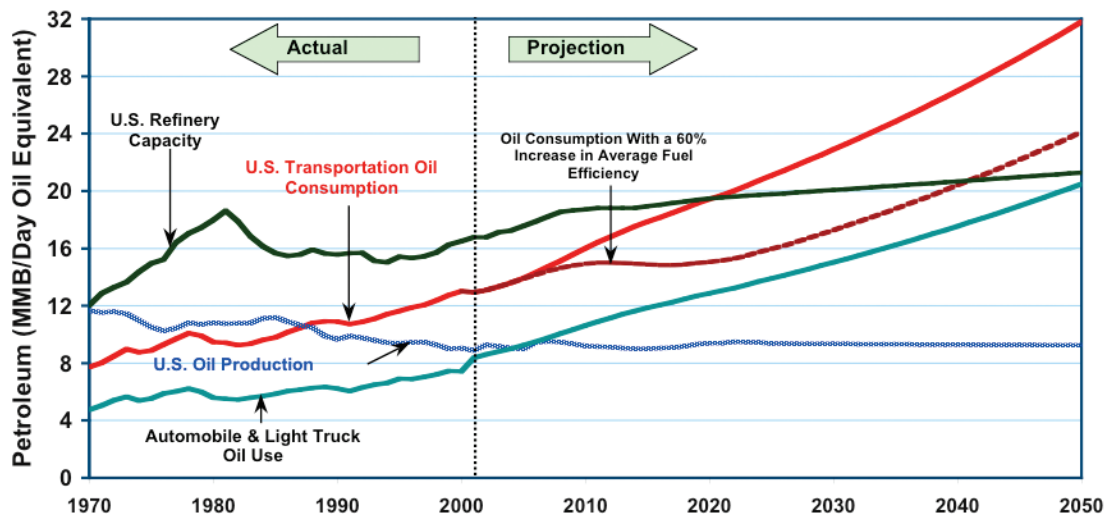


"...hydrogen can be produced from domestic sources -- initially, natural gas; eventually, biomass, ethanol, clean coal, or nuclear energy... One of the greatest results of using hydrogen power, of course, will be energy independence for this nation..."

—President George W. Bush
The National Building Museum
February 16, 2003

By 2025, the share of oil imports is expected to reach nearly 70% of the total oil consumed in the U.S. This imbalance presents a major concern for our nation's energy security. Two-thirds of the oil used in the U.S. goes to support our transportation fleet. To significantly reduce or end our dependency on oil imports, we must make a major change in the fuel used for the transportation sector. Even with the significant energy efficiency benefits that gasoline-electric hybrid vehicles and diesels can provide, we ultimately must find an alternative fuel that can be domestically produced.

Figure 2.1.1. U.S. Transportation Oil Gap



¹ References for this section are listed in Appendix C.

U.S. Dependence on Foreign Crude Oil and Transportation Fuel Imports

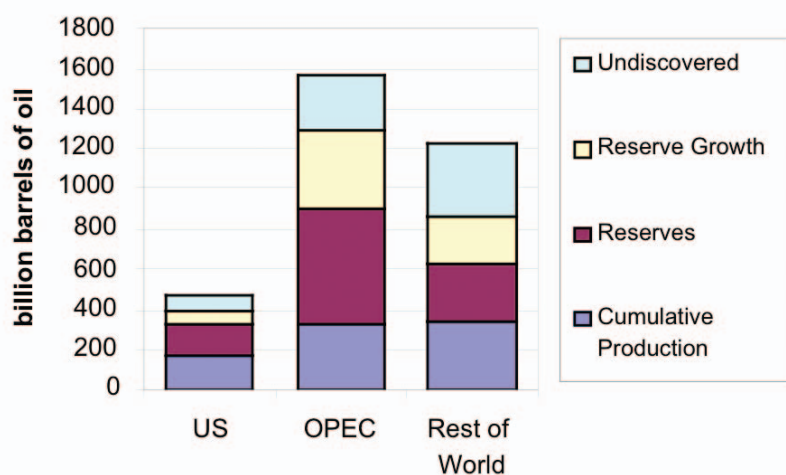
The divergence between oil used in the transportation sector and that produced and refined domestically (see Figure 2.1.1) is a result of a number of factors. U.S. crude production peaked in 1970, and has declined steadily since the mid-1980s. Even the addition of oil from other domestic sources has not changed this long-term decline in U.S. oil production. By the late-1980s, the transportation sector alone used more oil than was produced domestically. And by the late 1990s, the growing fleet of light duty cars and trucks (pickups, SUVs, and mini-vans) for personal transportation resulted in increased fuel use by light-duty vehicles.

The growing fuel consumption of the transportation sector not only has caused the U.S. to import more crude oil, but has forced a transition to a refined products import position. The fuel demand has outpaced the domestic crude oil refining capacity because of domestic refinery shutdowns, limited expansion of existing refineries and a lack of construction of new domestic refineries (the last new domestic refinery was constructed in the 1970s). As a result, increasing amounts of oil supplied for the U.S. transportation sector will be in the form of refined transportation fuels.

In an effort to manage the growing fuel demand, even a 60% increase in the average fuel efficiency for light-duty vehicles (to about 38 mpg) would not reduce the oil consumption, only slow the growth rate for a short period of time. Continued growth in the number of vehicles and the amount of travel will overwhelm the beneficial effects within a few years without continued vehicle fuel economy improvements. The addition of other domestic oil resources also provides a partial solution to meeting the nation's petroleum needs. However, the combination of efficiency improvements and increased domestic oil production does not close the transportation oil gap, which will widen again unless the transportation system eventually moves to a non-petroleum fuel.

From a global perspective, the finite levels of global petroleum resources further compound the energy security issue. As shown in Figure 2.1.2, a recent U.S. Geological Survey (2000) estimates that there are 3 trillion barrels of recoverable oil worldwide. About one-fourth has already been produced and consumed, while roughly an equal amount has been discovered and “booked as reserves.” Thus, the remaining half of the identified global oil resources are categorized as either reserve growth or probable, but undiscovered, resources. While data do not suggest an imminent global oil shortage, increasing petroleum consumption does present some concerns. World petroleum resources are finite and U.S. reserves are small compared to OPEC and the rest of the world. Although petroleum resources are relatively abundant, the geographic distribution is uneven and distant from most major consumers, and of particular concern, oil is concentrated in regions that have either political or environmental sensitivities.

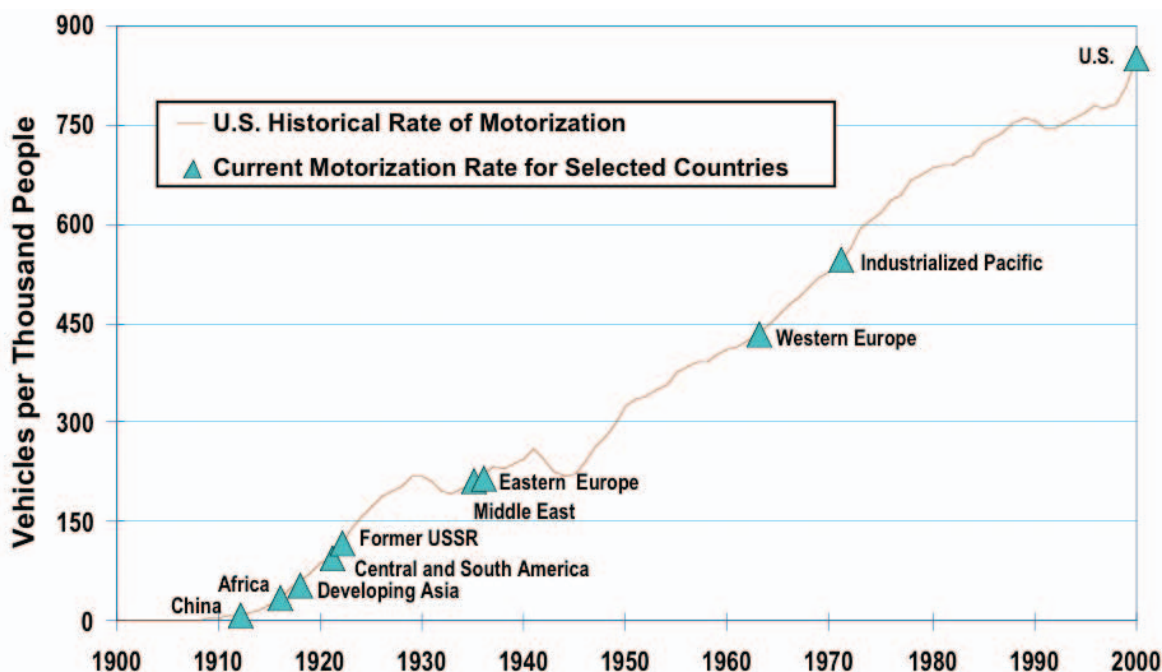
Figure 2.1.2. Global Distribution of Petroleum Resources



Global Transportation Trends

The worldwide growth in transportation as countries modernize and improve economically will accelerate oil consumption, resulting in the realization of a critical need to develop alternative energy sources. Some of the most rapidly developing countries are also the most populous, e.g., China and India. In terms of motor vehicles per thousand people, China is where the U.S. was in 1913 (Figure 2.1.3), and growing rapidly. During the 1990s, automobile registrations in China and India increased at an annual rate of 9.1% and 7.6%, respectively, while the growth rates for trucks and buses were 8.8% and 8.2%, respectively. For comparison, the U.S. growth rates for automobile registrations for the same decade declined by 0.5% while truck registrations (including SUVs, pickups, and mini-vans) and buses increased by 4.5%.

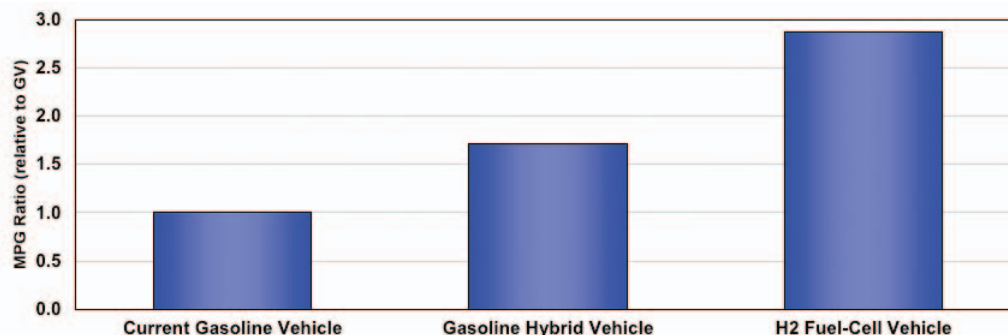
Figure 2.1.3. Current Global Motorization Rates Compared to U.S. Historical Rates



Advanced Vehicles Technologies Comparison

Improving the nation's energy security primarily depends on the degree that the transportation system can improve its energy efficiency and utilize domestic non-petroleum fuels. Success in the marketplace for advanced vehicle technologies will depend in part on the fuel economy advantages that can be achieved. Figure 2.1.4 (fuel economy estimates from Argonne National Laboratory) illustrates that fuel cell vehicles offer advantages over gasoline vehicles, even allowing for technological improvements in conventional powertrains.

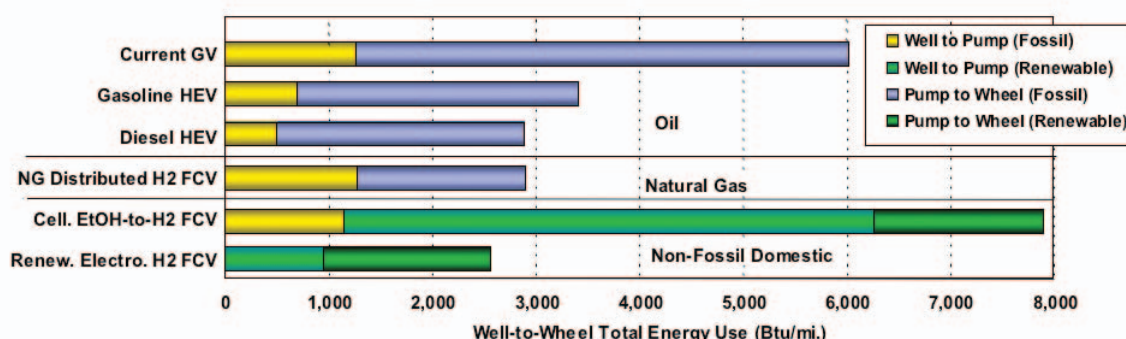
Figure 2.1.4. Relative Fuel Economies for Advanced Vehicle Technologies



Vehicle efficiency is not the sole measure used to compare the various technology options; upstream fuel processing, delivery and refueling needs must also be considered. Total energy well-to-wheels (WTW) cycle analysis is used to make informed decisions when comparing technology choices or applications within a given feedstock. The well-to-wheels analysis tells a complete energy story for hydrogen fuel cell vehicles as well as for alternative powertrains when different feedstocks are compared.

Figure 2.1.5 presents the full WTW energy use per mile of future light-duty vehicles using several prominent powertrain/fuel options. This figure shows that even with fuel production factored in, a fuel cell vehicle powered by hydrogen from natural gas offers improved efficiency over conventional gasoline-hybrid options. In addition, the fuel cell vehicle powered by hydrogen from renewable electrolysis offers improved efficiency over both gasoline- and diesel-hybrid vehicle options. This figure also illustrates that, as fuel cell vehicles and hydrogen infrastructure are developed, gasoline and diesel hybrid electric vehicles can offer significant energy savings over current gasoline vehicles. As mentioned, however, improving efficiency cannot fully address the long-term petroleum dependency problem; a move toward alternative energy resources is needed. For example, in addition to the two hydrogen-based options exhibited, hydrogen from solar, nuclear and renewable liquids (e.g., cellulosic ethanol) provides opportunities for reductions in petroleum use.

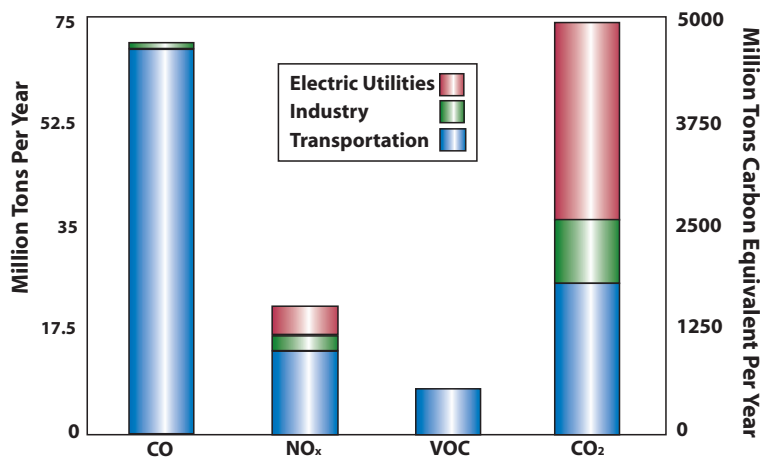
Figure 2.1.5. Comparative Vehicle Technologies: Well-to-Wheels Energy Use



2.2 Environmental Benefits

While addressing the energy security issue, we must also address our environmental viability. Air quality is a major national concern. It has been estimated that 60% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment. As shown in Figure 2.2.1, personal vehicles and electric power plants are significant contributors to the nation's air quality problems. Most states are now developing strategies for reaching national ambient air quality goals and bringing their major metropolitan areas into attainment with the requirements of the Clean Air Act. The State of California has been one of the most aggressive in their strategies and has launched a number of programs targeted

Figure 2.2.1. Emissions from Fossil Fuel Combustion



at improving urban air quality, since 90% of the state's population breathes unhealthy levels of one or more air pollutants during some part of the year.

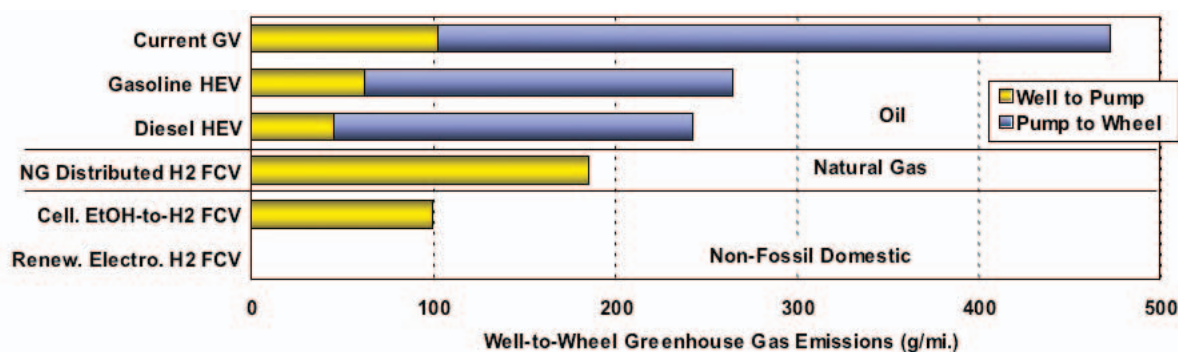
Criteria Pollutants

Internal combustion engines (both conventional and hybrid drives) will continue to have some on-road emissions. Although emission control technologies such as on-board diagnosis (OBD) systems can reduce the likelihood of vehicles that have high emissions rates due to on-road deterioration of engine performance and emission control devices, they cannot eliminate the so-called “high emitters.” Consequently, widespread use of fuel cell vehicles, because they are zero-emission vehicles and have no on-road emission deterioration, could be expected to have a measurable effect on reducing nitrogen oxides, volatile organic compounds, and particulate matter produced by light-duty vehicles. Although hydrogen production from certain feedstocks will generate some pollutants, emissions from stationary sources such as hydrogen production plants are easier to control and monitor than are deterioration in emissions control on vehicles.

Greenhouse Gases

Emission of greenhouse gases (GHGs), like carbon dioxide and methane, has been cited as a major global concern. Build-up of these gases in the atmosphere is thought to have detrimental effects on the global climate. Although there is not yet agreement on what the exact impact will be, when it will be realized, or how best to address the problem, there is agreement that emissions of these gases need to be reduced. Hydrogen offers a unique opportunity to address this problem, since carbon emissions can be decoupled from energy use and power generation; used in a fuel cell, the only emission is water. Efficient hydrogen production technologies and the possibility of carbon sequestration make natural gas and coal viable feedstock options, even in a carbon-constrained environment. In the case of renewable and nuclear options, greenhouse gases are essentially only the product of materials for construction, and of feedstock collection, preparation, storage, and delivery. The well-to-wheels analysis illustrated in Figure 2.2.2 confirms that hydrogen fuel cell vehicles can offer significant greenhouse gas benefits, even in the case of natural gas without carbon sequestration.

Figure 2.2.2. Comparative Vehicle Technologies: Well-to-Wheel Greenhouse Gas Emissions



2.3 Economic Competitiveness

Abundant, reliable, and affordable energy is an essential component in a healthy economy. When energy prices spike, as has occurred several times recently due to supply interruptions and/or high demand, Americans suffer economically, particularly those in lower-income brackets. Looking at the expenditures for energy across all income levels, the average percentage of personal income that was spent on energy in 2003 was 4.8% (U.S. Department of Commerce, Bureau of Economic Analysis). Lower-income families spend nearly as many dollars as those in higher-income brackets to heat their homes and fuel their cars (the average energy expense for low-income families is 12.6% of income). The number of American families requesting assistance with heating bills has risen significantly; in the winter of 2000, 5 million families applied to receive Low Income Home Energy Assistance. Hydrogen offers unique opportunities to drastically increase the efficiency with which we generate and use energy. And because it can be produced from a wide variety of domestically-available resources, we can reduce the impact of externalities on energy prices. Hydrogen's diversity in production, and flexibility in use, also opens the door for new players in energy markets. In addition to the energy security benefits, this has economic equity implications due to broadening energy choices and increasing competition.

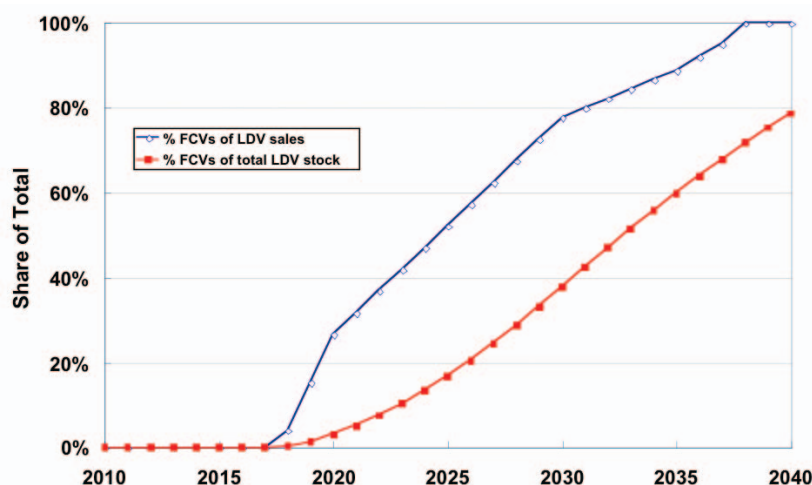
The technical and economic success of hydrogen-based distributed energy systems will catalyze new business ventures. Hydrogen power parks will provide an economic development path for the integrated production of energy services such as electricity, transportation fuels, and heating and cooling. This will lead to the creation of high-tech jobs to build and maintain these systems. Hydrogen also offers a wide variety of opportunities for the development of new centers of economic growth in both rural and urban areas that are currently too far off line to attract investment in our centralized energy system.

The competitiveness of U.S. industry is also of vital importance to the well-being of our people and of the nation as a whole. For example, the U.S. auto industry is the largest automotive industry in world, producing 30% more vehicles than the second largest producer, Japan. The auto industry is a highly productive one (ranked fourth) and is accompanied by relatively high levels of compensation; in 1998, the average autoworker earned \$65,000, compared to \$48,000 for the average in the manufacturing sector and \$38,000 for the average worker nationwide. The auto industry is also a major exporter, accounting for 12% of all non-agricultural exports. For every worker directly employed by an auto manufacturer, there are nearly seven spin-off jobs. America's automakers are also among the largest purchasers of aluminum, copper, iron, lead, plastics, rubber, textiles, vinyl, steel and computer chips. The auto industry ranks near the top of U.S. industries in terms of investment in R&D. Remaining competitive in the international market is essential to the auto industry and the U.S. economy as a whole.

2.4 Potential Impact of Fuel Cell Vehicle Introduction

The rate of market penetration of the fuel cell vehicle will determine its impact on future U.S. petroleum consumption. A penetration scenario is provided in Figure 2.4.1, which is based on a market model of past U.S. transportation fuel transition, and assumes the necessary RD&D to overcome the technical and cost barriers is completed by 2015. If the commercialization decision is positive, then vehicle sales could begin three years later in 2018. Meeting the milestones in this plan means that the fuel cell vehicles are not just competitive with conventional vehicles in both performance and cost, but also provide additional energy and environmental benefits, making rapid market acceptance feasible such that by 2025 half of all new light duty vehicle sales are fuel cell vehicles. Rapid market penetration could also be stimulated by government policies that provide incentives to consumers.

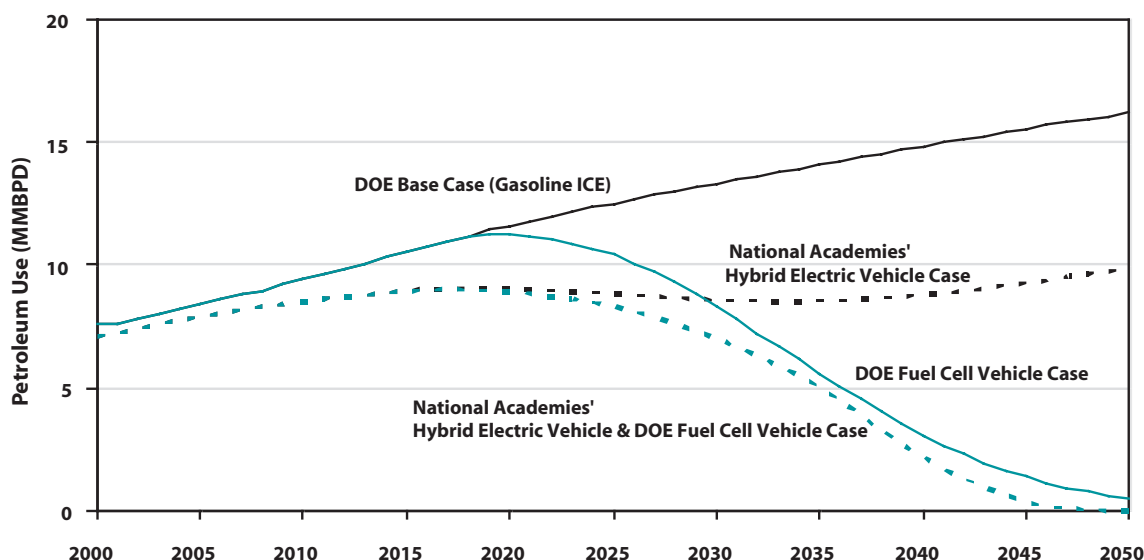
Figure 2.4.1 A Scenario: Market Penetration of Fuel Cell Vehicles



Based on the optimistic scenario described above, the impact of fuel cell vehicle and gasoline hybrid vehicle penetration in reducing petroleum use is illustrated in Figure 2.4.2. As shown, the gasoline hybrid vehicle will temporarily slow the growth in oil consumption. But as the population continues to grow, gasoline demand will return to historic consumption growth rates. In contrast, the penetration of hydrogen fuel cell vehicles, or a combination of gasoline hybrids and hydrogen fuel cell vehicles, will begin to slow petroleum use and eventually cause the decline approximately in 2025, if a substantial number of light duty fuel cell vehicles are on the road.

The rate of projected transition of fuel use illustrated here was compared to historical rates of fuel transition in the U.S. in an analysis by Argonne National Laboratory. This comparison illustrated that this rate is well within the range of transportation fuel switch transition rates that have occurred in the U.S. over the last two centuries. Note that the projected eventual elimination of oil use in light duty vehicles would not by itself mean that oil use in the transportation sector would disappear, as oil would still be needed for other parts of the transportation system. However, our reliance on foreign sources of oil would be significantly reduced.

Figure 2.4.2. Potential Impact of Fuel Cell Vehicles on U.S. Light-Duty Vehicle Petroleum Use



Domestic Resources

One of the principal energy security advantages of hydrogen as an energy carrier is diversity – the potential for producing it from a variety of domestic resources. But do we have enough domestic resources to provide the hydrogen we need? Assuming an average vehicle mileage of 60 mpg, 150 million fuel cell vehicles (approximately one-half of the U.S. light-duty vehicle fleet) will require around 40 million tons of hydrogen annually. In a worst case situation, we would need to produce all of this hydrogen from just one resource, for example, natural gas. Current annual U.S. consumption is 495 million tons of natural gas. An additional 130 million tons of natural gas would be needed to produce the 40 million tons of hydrogen; this represents a 27% increase in consumption. As of January 2000, remaining technically recoverable natural gas reserves were estimated at 28 billion tons, or 46 times the needed annual consumption. If, instead, we produced the 40 million tons of hydrogen from our abundant domestic coal resources (approximately 4 trillion recoverable tons), annual coal consumption would increase by less than 30%. Other options include:

- **Biomass:** The current agricultural and forest products residues, organic municipal solid waste, urban tree residues, livestock residues and potential energy crops would be sufficient to produce 40 million tons of hydrogen.
- **Wind-Electrolysis:** 555 GW of installed wind would be needed to produce 40 million tons of hydrogen. Only around 4 GW of wind is currently installed in the U.S., but this figure is growing rapidly with improved designs and lowering costs. The estimated wind capacity in the U.S. is around 3,250 GW; 555 GW represents the available capacity of North Dakota.
- **Solar-Electrolysis:** 740 GW, approximately 3,750 square miles (equivalent to 3% of the land area of Arizona), of flat-plate photovoltaics would be needed to produce 40 million tons of hydrogen.
- **Nuclear energy:** Nuclear power can also provide electricity to produce hydrogen via electrolysis of water. Around 200 conventional 1 GW_e reactors would be needed to produce 40 million tons of hydrogen annually. This would require tripling the number of currently-deployed nuclear reactors. Instead of generating electricity, advanced nuclear reactor concepts (Gen IV) could be used to produce heat that would permit high-temperature electrolysis or thermochemical cycles. In this case, only 125 new reactors would be needed.

The following provides a brief description of the key attributes of some of the various resources from which hydrogen can be produced.

Natural Gas. One of the most widely used energy sources is natural gas. It is used for space heating and cooling, water heating, cooking, electricity generation, transportation, and in industry provides the base ingredients, such as hydrogen, for such varied products as plastics, fertilizers, anti-freeze, and fabrics. Reforming of natural gas makes up nearly 50% of the world's hydrogen production and is the source of 95% of the hydrogen produced in the U.S. Steam reforming is a thermal process, typically carried out over a nickel-based catalyst that involves reacting natural gas or other light hydrocarbons with steam. Large-scale commercial units capable of producing hydrogen are available as standard “turn-key” packages.

Coal. Another widely used energy source is coal; major uses include electricity production, iron and steel manufacturing, and cement production. Currently, more than 70 gasification plants are operating throughout the world using coal or petroleum coke as a feedstock. Advanced systems are also the subject of RD&D. DOE's FutureGen Initiative, led by the Office of Fossil Energy, is a plan to build a prototype of the fossil fuel power plant of the future—a plant that combines electricity generation and hydrogen production with the virtual total elimination of harmful emissions and greenhouse gases. Current plans call for the 275 MW plant to be designed and built over the next ten years, then operated for at least five years beyond that.

Biomass. Renewable feedstocks can be used to produce hydrogen, either directly or through intermediate carriers (e.g., ethanol). Some biological organisms can produce hydrogen through fermentation. Alternatively, fermentation could be used to produce methane or sugar alcohols that can be reformed to hydrogen. Thermal processing (pyrolysis or gasification) can also be used and the techniques for biomass and fossil fuels (reforming, water gas shift, gas separation) are similar. Approximately 10 kg of biomass are required to produce 1 kg of hydrogen. For comparison, around 3 billion gallons of ethanol is produced for fuel use and 200 million tons of biomass is used to produce heat, power and electricity annually.

Wind. In some parts of the country, wind energy is supplementing more conventional forms of electricity production. California now produces more than 10% of the world's wind-generated electricity. Wind turbines have been connected to electrolysis systems that can operate with high efficiency (~70%) to produce hydrogen. Construction costs have dropped to about \$1 million per MW, which works out to about 4 to 6 cents per kWh and this price is expected to drop even further in the coming years.

Solar. Sunlight can provide the necessary energy to split water into hydrogen and oxygen. Photovoltaic arrays can be used to generate electricity that can then be used by an electrolyzer to produce hydrogen. Some semiconductor materials can also be used to directly split water in a single monolithic device, eliminating the need for separate electricity-generation and hydrogen-production steps. Similarly, a number of biological organisms have the ability to directly produce hydrogen as a product of metabolic activity. Finally, solar concentrators can be used to drive high-temperature chemical cycles that split water. Like wind, there are huge solar resources in the U.S., especially in the southwestern portion of the nation, where one acre of land could potentially supply 15,000 kilograms of hydrogen per year using today's commercial photovoltaics.

Nuclear Energy. Current nuclear technology generates electricity that can be used to produce hydrogen via electrolysis of water. Advanced nuclear reactor concepts (Gen IV) are also being developed that will be more efficient in the production of hydrogen. These advanced technologies provide heat at a temperature that permits high-temperature electrolysis (where heat energy replaces a portion of the electrical energy needed to dissociate water) or thermochemical cycles that use heat and a chemical process to dissociate water. The thermodynamic efficiencies of thermochemical cycles for the direct production of hydrogen with Gen-IV reactors may be as high as 45%. This contrasts with the 33% efficiency of the existing reactors for electric power production. By bypassing the inefficiencies of electric power production and electrolysis losses, the overall efficiency of converting heat energy to hydrogen energy is increased significantly.

Fusion Energy. Fusion power, if successfully developed, could be the ultimate source of a clean, safe, abundant, and carbon-free domestic resource for hydrogen production. The DOE Office of Science will lead the U.S. efforts in the International Thermonuclear Experimental Reactor (ITER) project, whose mission is to demonstrate the scientific and technological feasibility of fusion energy within the next 35 years. The United States will work with Great Britain and several European nations, as well as Canada, Japan, Russia and China, to build a fusion test facility and create the largest and most advanced fusion experiment in the world. Fusion energy releases vast amounts of heat, which can be used to produce hydrogen from water by means of thermolysis (thermally driven dissociation of water) or by thermochemical cycles.

The reality is that a transition from petroleum to hydrogen will be gradual and a variety of technologies and feedstocks will be used to meet the growing demand. Near-term production needs will likely begin with natural gas. Electrolysis will find markets where lower-cost and off-peak electricity is available. Biomass could meet mid-term needs in regions where agriculture and forest products are the mainstay. Over time, we will see the costs of renewable power generation technologies drop and gain growing shares of the electrolysis markets. Direct water splitting and high temperature technologies will begin to be demonstrated and find their place in

the market, as well. The share of each technology will be a function of cost, regional markets and resource availability. Policy and environmental constraints will also dictate the penetration rates of the various options.

2.5 Realizing the Benefits

In addition to addressing the major challenge of energy security, hydrogen fuel cell systems can address many of our nation's other energy-related needs. To meet our growing electrical demands, it is estimated that electricity generation will have to increase by 2% per year. At this rate, 330 GW of additional electricity generation capacity will be needed by 2020. Along with an aging transmission and production infrastructure, requirements for reliable premium power and market deregulation, this increasing demand opens the door for hydrogen power systems.

Hydrogen power systems provide unique opportunities for increasing the diversity of the electricity market. Currently, grid stability and intermittency issues are major limitations for the penetration of renewables like wind and solar into the electricity market. By combining these generation technologies with hydrogen production and storage, intermittent renewables could potentially capture a larger share of the power production market without major upgrades to the existing grid.

Hydrogen systems can be extremely efficient over a large range of sizes (from one kilowatt to hundreds of megawatts). Some systems can achieve overall efficiencies of 80% or more when heat production is combined with power generation. Additionally, smaller-scale distributed hydrogen systems offer combined heat, power and fuel opportunities. Fuel cell systems integrated with hydrogen production and storage can provide fuel for vehicles, energy for heating and cooling, and electricity to power our communities. These clean systems offer a unique opportunity for energy independence, highly reliable energy services and economic benefits.

While enormous, the benefits of a hydrogen economy cannot be realized overnight. A transition is necessary; however, hydrogen has the flexibility and robustness to meet the challenge. To realize the benefits, several things must occur. Fuel cell technologies and hydrogen storage systems must be advanced so that hydrogen fuel cells can be a cost-competitive choice for the consumer when they go to buy a new vehicle, or when communities evaluate energy options. Hydrogen production options require additional research and implementation for cost parity with today's fuels. And the existing hydrogen infrastructure needs to grow to a point where all consumers can conveniently obtain hydrogen. If we are successful in developing hydrogen technologies to their full potential, we could significantly reduce U.S. demand for oil and greenhouse gas emissions.